Continuous for Live Load: A Texas Historical Perspective

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Abstract

A significant number of engineers in the United States have designed and continue to design precast prestressed concrete bridges that carry non-composite dead loads as simple spans, but are made "continuous for live load." Often such engineers are surprised to learn that the state of Texas, with the lowest bridge construction costs in the nation, and approximately 50,000 total inventoried bridges, one-fifth of which contain precast prestressed concrete superstructures, has very few precast prestressed concrete bridges made "continuous for live load." This paper presents a chronology and a survey of the use of this method of bridge construction in Texas with emphasis on design philosophy, design details, and the existing conditions of elements that are critical to maintain the live load continuity of selected in-service bridges.

Introduction

Historically, Texas has a reputation for low bridge construction costs[3]. Much of the cost savings contributing to that reputation is directly due to extensive use of precast, prestressed concrete superstructures. Most of these superstructures are designed as simple spans with expansion joints at the ends of each span, or simply supported girders supporting a longitudinally continuous reinforced concrete deck over one to three interior supports. The latter method, is currently the standard in Texas.

Of the 32,547 on-system bridges in the Texas Bridge Inspection Database, 325 have superstructures listed as reinforced concrete slab on precast, prestressed concrete beams made continuous for live load. This type of structure is designed and detailed to resist non-composite loads by simple span action and composite loads (predominantly live plus impact loads) by continuous beam action. For this pseudo-continuous action to occur the connections at the

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[3]Supporting data has been taken from "2001 [BRIDGE] CONSTRUCTION UNIT COST FOR FY 2003 APPORTIONMENT," Attachment I, of an unpublished Federal Highway Administration (FHWA) report to the US Congress regarding the FY 2003 Apportionment of Highway Funds authorized by the TEA 21 legislation. For the FY 2003 apportionment, Texas is ranked 2 out of 52, in terms of total construction dollars per square foot of on-system bridges, and 5 out of 52, in terms of total construction dollars per square foot of off-system bridges — based on averages of FY 1999, 2001, and 2002 unit costs.

interior bents must be able to develop a tensile force in the concrete deck, and an equal but opposite compressive force in the bottom of the prestressed concrete beams, which when multiplied by the distance between the center of action of the forces equals or exceeds the negative moment produced by composite loads. Also, the same section must be able to resist the positive moment produced by live load(s) on remote spans, time-dependant deformations (due to creep and shrinkage), and thermal effects (due to seasonal ambient temperature and temperature gradient) which may occur after the placement of the bridge deck. For these latter moments the tensile and compressive forces switch place and have different magnitudes.

This paper discusses the past practice in Texas of providing for the bottom beam end compression force and tension force required to make prestressed concrete beam bridges continuous for live load. The reason for this narrow focus is the relative ease with which the tension force and compression force can be provided for in the slab and the concomitant difficulty with which the compression force and tension force can likewise be developed in the bottom of the beam ends. To address the methods used to provide continuity this paper presents a sample of such bridges, built in Texas from 1962 to 1990, and discloses salient details of the archived construction documents, thereby documenting these historical artifacts of precast, prestressed concrete bridges made continuous for live load. Discussion of these and other issues that have resulted in the TxDOT Bridge Division's opinion that "the disadvantages outweigh the advantages of designing continuous for live load,"[4] effectively eliminating this construction practice in Texas is also presented.
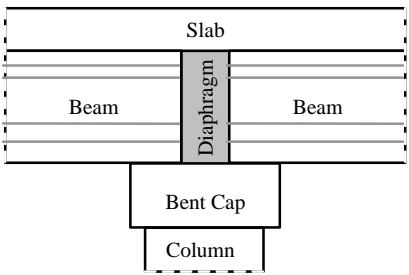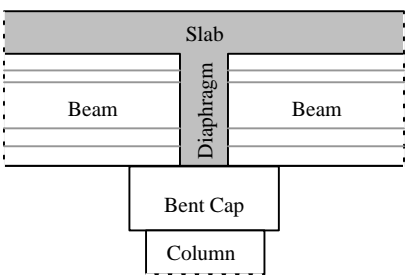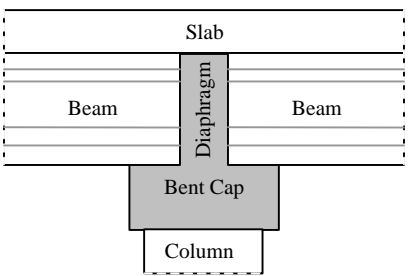
Continuity Diaphragms

The authors collected and inspected construction documents for each bridge in the sample and examined the details of the continuity diaphragms that are essential to the development of live load continuity. In many of these plan sets, previously unidentified bridges were found which also have live load continuity details. These bridges were added to the sample, increasing its size. A significant number of the bridges in the sample were found not to be continuous for live load. These bridge identifications were compiled to aid in correcting the TxDOT Bridge Inspection Database. Thus, data was collected from a pseudo-random sample of the subject bridges for a wide and largely encompassing range of common practice.

The diaphragms used to provide continuity for all of the structures within the sample are divided into three main types/systems; Simple Diaphragms, Monolithic/Slab Diaphragms, and Bent Cap Diaphragms. These three types of diaphragms are explained further in Table 1, and the following text. There are many similarities between the three different types of diaphragms. All three systems show connection of beam ends to the diaphragms via steel protruding from the beam ends and extending into the diaphragms. The steel protruding from the beam ends consists of either steel prestressing strands, reinforcing bars, or a combination of the two. The beam ends are typically embedded into the diaphragm, and are not chamfered like the ends of non-embedded beams.

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[4] TxDOT, "Section 23 — Prestressed Continuous for Live Load I-Beam Spans," *Bridge Design Manual* http://manuals.dot.state.tx.us:80/dynaweb/colbridg/des/@Generic__BookView, p. 7-96, 12/2001.

Table 1. Diaphragm Types

Diaphragm Type	Diagram
Simple Diaphragms	
Monolithic Slab/Diaphragms	
Bent Cap Diaphragms	

Simple Diaphragm

The simple diaphragm method is the oldest system found. It was used in the late 60's to early 70's. It consists of a diaphragm shaped and reinforced much like the midspan diaphragm used to prevent lateral-torsional induced overstress during slab placement (and also once thought necessary to achieve transverse distribution of the live load). Steel reinforcing bars three inches from the bottom of the beams extend from the end of the beam into the diaphragm forming a 90 degree or 180 degree hook, often around a reinforcing bar running continuous or discontinuous along the centerline of the diaphragm. In some instances the hooks are also welded to the additional reinforcement bar. This latter bar is usually the only reinforcement extending through the intersection of the beam faces and the diaphragm. Between beam ends the diaphragms have longitudinal (along bent) and transverse (vertical) reinforcement much like the reinforcement used in midspan diaphragms, with the longitudinal bars being discontinuous through the intersection with the beams and the diaphragms. The thickness of the diaphragm is typically greater than the distance between beam ends, allowing for the beam ends to be embedded a few inches into the diaphragm.

Monolithic Slab/Diaphragms

In the monolithic slab/diaphragm system the diaphragms are cast monolithically with the slab. This system, used primarily from the mid 70's to mid 80's, is the most common method for providing continuity, having been found in 55% of the structures studied. The reinforcement for these diaphragms is similar to the reinforcement used in the simple diaphragms discussed above, with the exception of the additional reinforcement running between the diaphragm and the slab. The bars protruding from the beam ends into the diaphragm have 90 degree hooks enclosing a #8 deformed reinforcing bar that runs along the centerline of the diaphragm. Additionally, the harped prestressing strands protrude 2 inches from the beam ends and are thus embedded in the diaphragm.

Bent Cap Diaphragms

In the third system the stems of inverted-T bent caps act as the diaphragms, although the "ledge" of the inverted-T is cast first, as the cap upon which the girders are erected, and then the stem concrete is placed prior to the slab. This is the most recently used system, having been used in bridges built from the mid to late 70's to 1990. It is the second most common system, having been found in 33% of all of the structures studied. In this system the diaphragms are reinforced less like a midspan diaphragm and more like a typical inverted-T bent cap. The connections between the beams and the cap consists of either a reinforcing bar and protruding harped prestressing strands, or both harped and straight strands, extending into the diaphragm.

Connection Details

Figures 1-5 show drawings of the various connection details, with generic labels for the dimensions. Tables 2-5 show dimensional and other data for each of the structures studied.
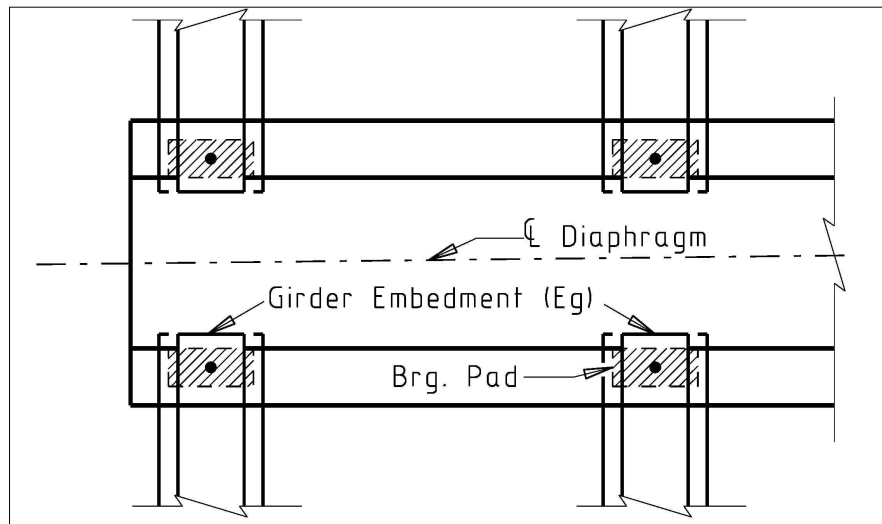

Figure 1. Beams Embedded Into the Diaphragm (Plan View)
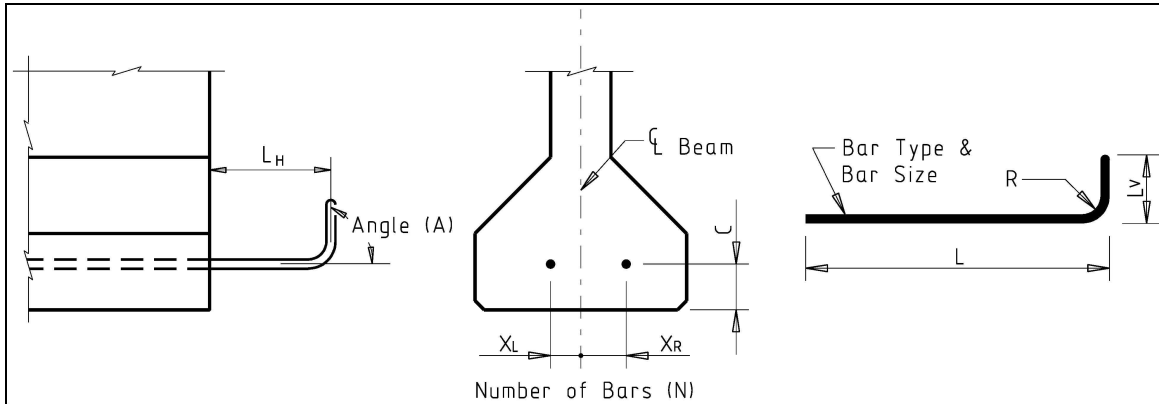
Figure 2. Structural Anchor Dimensions
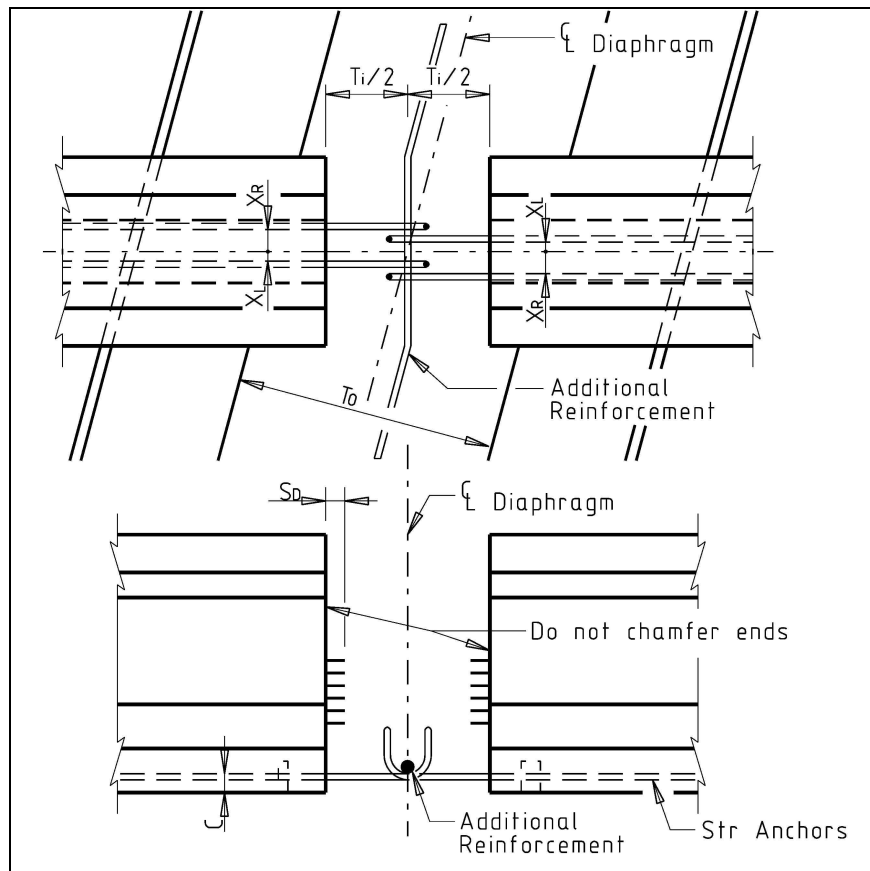

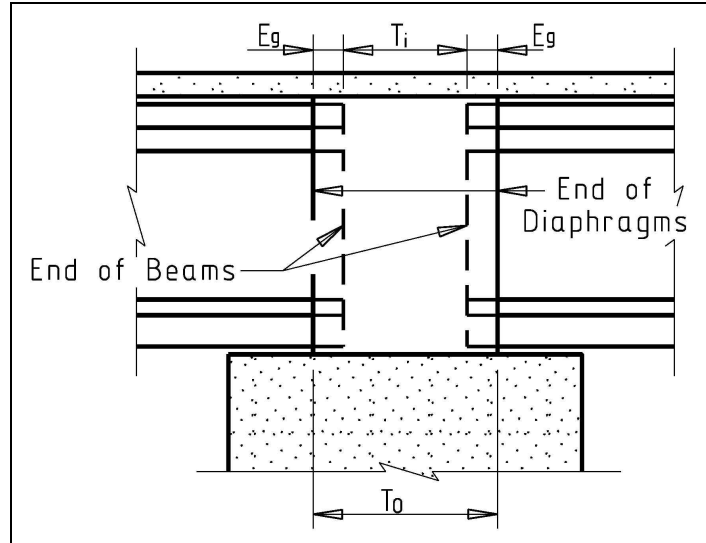**Figure 3. Plan and Elevation Views of Connecting Beam ends**

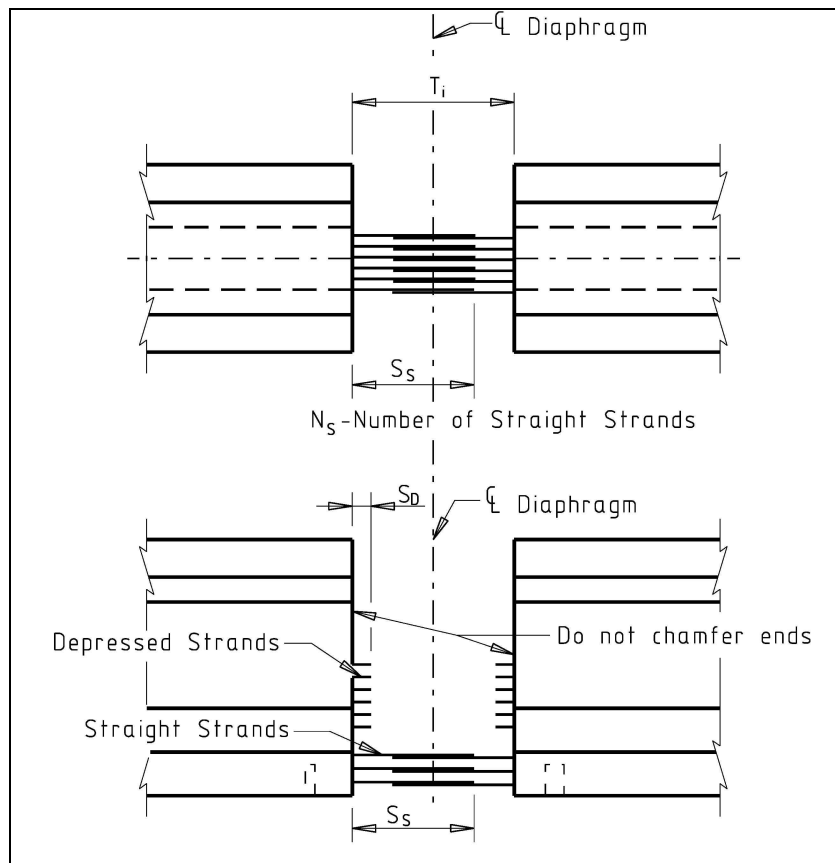**Figure 4. Diaphragm Thickness and Girder Embedment**

**Figure 5. Plan and Elevation Views of Connecting Beam
Ends Using Straight Prestressing Strand Reinforcement**

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Table 2. Simple Diaphragm Dimensions

Bridge NBI Number	Year Built	Number of Bars	Bar Size	Bar Type	L (in)	L_H (in)	R (in)	A (degrees)	X_L (in)	T_i (in)	T_O (in)
14227001513189	1962	2 [a]	#7	Deformed	28	14	3	90	2	6	12
14227001513190	1962	2 [a]	#7	Deformed	28	14	3	90	2	6	12
12102027107316	1968	3 [b]	#8	Deformed	34.5	4.5	4.5	90	6	6	12
12102027107317	1968	3 [b]	#8	Deformed	34.5	4.5	4.5	90	6	6	12
12102027116364	1970	2	1/2"	Smooth/Round	18	3	3	180	2	8	8-19
12102027116481	1970	2	1/2"	Smooth/Round	18	3	3	180	2	8	8-19

The following dimensions are common for all structures included in this table (Table 2):

L_V = 6 inches   C = 3 inches X_R = 4 inches   Additional Reinforcement = #8 bar

[a] The hooks extending from the ends of these beams are bent so that they are parallel to the centerline of the diaphragm and there is no additional reinforcement through the diaphragm.

[b] These beams have one bar running 2 inches to the right of the beam centerline, one bar X_R to the right, and one bar X_L to the left of this middle bar.

Table 3. Monolithic Slab/Diaphragm Dimensions

Bridge NBI Number	Year Built	Bar Size	Bar Type	L_H (in)	C (in)	T_i (in)	T_O (in)	E_G (in)
18057044202188	1974	1"	Square/Smooth	4	3	8	14	3
18057237403179	1974	1"	Square/Smooth	4	3	9	15	3
18057237403180	1974	1"	Square/Smooth	4	3	8	14	3
18057237403183	1974	1"	Square/Smooth	4	3	8	14	3
18057237403184	1974	1"	Square/Smooth	4	3	8	14	3
18057237403185	1974	1"	Square/Smooth	4	3	8	14	3
18057237403186	1974	1"	Square/Smooth	4	3	8	14	3
18057237403187	1974	1"	Square/Smooth	4	3	8	14	3
05096006704132	1980	#9	Deformed	4	3	6	12	3
07134014108154	1980	#10	Deformed	4	3	6	12	3
07134014108156	1980	#10	Deformed	4	3	6	18	6
07134014108159	1980	#10	Deformed	4	3	6	12	3
07134014108153	1981	#10	Deformed	4	3	6	12	3
14011026506081	1984	#9	Deformed	4	3.5	6	24	9
09014032005085	1985	1"	Smooth/Round	4	3	6	12	3
09014032005086	1985	1"	Smooth/Round	6	3	10	12	1
01092004718232	1986	1 1/8"	Smooth/Round	4	3	6	9-12	3-6
05096006704129	1986	#9	Deformed	4	3	6	27	10.5
05096006704130	1986	#9	Deformed	4	3	6	27	10.5
05096006704133	1986	#9	Deformed	4	3	6	27	10.5
05096006704134	1986	#9	Deformed	4	3	6	27	10.5

The following dimensions are common for all structures included in this table (Table 3):

Number of Bars = 2   L = 48 inches L_V = 7 inches

A = 90 degrees   R = 3 inches S_D = 2 inches

X_L = 2 inches X_R = 4 inches   Additional Reinforcement = #8 Bar

Table 4. Dimensions for Inverted T Bent Cap Diaphragms With Bar Reinforced Connections

Bridge NBI Number	Year Built	T_i (in)	T_O (in)
09014032005084	1985	32	38
09014032005398	1985	32	38
09161016201084	1990	26	32

The following dimensions are common for all structures included in this table (Table 4):

Number of Bars = 2	Bar Size = #9	Bar Type = Deformed
L = 72 inches	L_V = 12 inches	L_H = 20 inches
R = 3 inches	A = 90 degrees	C = 3 inches
X_L = 2 inches	X_R = 4 inches	S_D = 2 inches
E_G = 3 inches		

Table 5. Dimensions for Inverted T Bent Cap Diaphragms Prestressing Strand Reinforced Connections

Bridge NBI Number	Year Built	S_S (in)	N_S	T_i (in)	T_O (in)
18057035305127	1976	38	12-40	38	42
18057035305128	1976	16	16	20	24
18057035305130	1976	32	16	32	36
18057035305139	1976	38	14-44	38	42
18057035305200	1976	38	14-46	38	42
18057035305201	1976	38	10-44	38	42
18057035305202	1976	38	12-44	38	42
01092004718232	1981	28	20-24	32	36

The following dimensions are common for all structures included in this table (Table 5):

Number of Bars = 0	S_D = 2 inches	E_G = 2 inches

All prestressing strands are 1/2 inch diameter Grade 270 strands.

Time Distribution of the Continuity Diaphragm Systems

The structural details studied indicate that the approach to providing for the bottom beam end compression force and tension force required for live load continuity progressed over the years. It began with the simple diaphragm and progressed to the monolithic slab/diaphragm, and finally to the inverted-T bent cap diaphragm. The use of the simple diaphragm appears to have ended before the monolithic slab/diaphragm was widely used. The time frames in which the monolithic slab/diaphragm and the inverted-T bent cap diaphragm were used, however, overlap. This indicates that, unlike the simple diaphragm, the monolithic slab/diaphragm was not abandoned completely with the advent of the inverted-T bent cap. Table 6 contains a timeline with the frequency of occurrence of the diaphragm types used in the sampled bridge set indicated.

Table 6. Frequency of Diaphragm Use Over Time from Sampled Data

System	Year Built																											
	1962	63	64	65	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
Simple	2					2		2																				
Monolithic														8				4	1			1	2	5				
Bent Cap														7					1				2					1

Existing Condition of the Subject Bridges

While the conditions of the bridges will depend on many factors that are unrelated to the type of continuity diaphragm used, some major trends have been noticed from condition surveys and observations of the bridges studied.

At least five out of the six bridges using the simple diaphragm have minor cracking and spalling on the face of the continuity diaphragms; no information was obtained on the sixth bridge.

The most common problem with the use of the monolithic slab/diaphragm observed is minor spalling and cracking of the diaphragm, much like what was seen on the simple diaphragms. There is some level of damage to the diaphragm on all of the structures that were inspected. The damage varies widely from minor spalls and cracks to having the steel inside the diaphragm exposed.

The inverted-T bent cap diaphragms show the least damage of the three types. The most common damage observable on these structures is traverse cracks in the deck above the diaphragms, although this was only seen on four out of the eleven structures observed. While the connections current conditions are related to design and construction, the time the bridges have been in-service may also be a factor. The most recently built bridges, the inverted-T bent cap bridges, would be expected to show the least damage, should the damage be time-dependant. Comparing the condition surveys of inverted-T bent cap diaphragms and the monolithic slab/diaphragms that were built concurrently indicates that the bent cap diaphragms are less damaged than the monolithic slab/diaphragms, which may indicate that the bent cap diaphragms are the more robust system. Figures 6-11 show the type of damage that are common among the structures studied.

Figure 6. Severely Cracked Beam Ends at Continuity Diaphragm
Bridge NBI 14227001513189

Figure 7. Cracking of the Diaphragm Face at Beam Intersection
Bridge NBI 14227001513189

Figure 8. Cracking of the Beam and Diaphragm at Their Intersection
Bridge NBI 14227001513189

Figure 9. Cracking of the Diaphragm Face at Beam Intersection
Bridge NBI 14011026506081

Figure 10. Cracking of the Exterior Beam and Diaphragm at Their Intersection
Bridge NBI 14011026506081

Figure 11. Aesthetic Continuous Beam Connection
Bridge NBI 14011026506081

Efficacy of the Continuous for Live Load Concept

According to the TxDOT Bridge Design Manual, "[m]ost problems with simple prestressed concrete beam spans are caused by leakage through the deck joints at the ends of each span. In an attempt to circumvent this problem, continuous for live load designs were introduced in the early 1960s."[5] So, the rationale for the continuous for live load philosophy was not to achieve longer spans for precast prestressed concrete beams without increasing superstructure depth, as one might think, but rather to decrease the amount of deterioration occurring at bridge joints and the underlying bridge substructures by reducing the flow of water through the structure at these locations.

Longer spans could more economically be achieved using slightly higher concrete strengths and 2 to 4 more prestressing strands. This is due in part to the fact that longer spans result in a lower ratio of composite load to total load moments as well as the fact that the provision of pseudo-continuity introduces additional construction complications.

To illustrate the design impact of providing this pseudo-continuity the authors inspected the details and analyzed the last bridge made "continuous for live load" in Texas for the moments at midspan. Table 7 displays the results of this analysis. The analysis of the continuous structure uses the center-to-center of bents as the span length, whereas the simply supported beam analysis uses center-to-center bearing distance, a minor difference.

The rail and overlay loads are carried by the composite section, as is the live plus impact load. The ratio of the total moments on the composite section of the continuous for live load superstructure to the simple span superstructure is 0.827, a "savings" of 17% in terms of moment. However, the same non-composite dead load must be carried by both configurations and this load produces the largest portion of the stresses in the prestressed concrete bridge girders. The ratios of composite load to total load moments are 0.378 and 0.424 for the continuous for live load superstructure and the simple span superstructure, respectively—a "savings" of only 11% in terms of moment, and much less in terms of girder stress. The simple span superstructure design required only 4 more strands (6.45% more) and a slightly higher initial concrete strength.

Not only is a continuous beam more complicated to analyze than a simple span but the detailing of the beam ends, with their requisite protruding anchorage bars or strands, and complicated erection of the girders is not worth the savings in prestressing steel. Additionally, the increased size and amount of longitudinal reinforcement required in the slab to handle the negative moments above the bents may not accommodate precast concrete sub-deck panels, further complicating construction. The use of precast deck panels can save a significant amount of time

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[5] TxDOT, "Section 23 — Prestressed Continuous for Live Load I-Beam Spans," *Bridge Design Manual* http://manuals.dot.state.tx.us:80/dynaweb/colbridg/des/@Generic__BookView, p. 7-95, 12/2001.

and can reduce the contractor's liability insurance, reducing construction costs. The purported benefits of continuous for live load design come with a heavy price if they limit the use of the precast deck panels. The only apparent advantage is an aesthetic advantage resulting from the supposed elimination of vertical lines at beam ends (see Figure 10), an advantage that is totally subjective, and is often compromised by the cracking that occurs at the beam/diaphragm interface.

The efficacy of the continuous for live load concept has been undermined by a number of flaws. Though not the focus of this paper the tension force in the slab typically produces multiple transverse cracks in the negative moment region. This cracking would likely be more severe if precast concrete sub-deck panels were used because the panel terminations near the beam ends would encourage this type cracking. These cracks compromise the durability of the negative moment region of the slab. Also the tension force in the bottom of the beam ends and in the continuity diaphragms is not readily determined from simply a continuous beam analysis. The greater part of this force is a combination of effects from time-dependent beam camber and shrinkage, as well as from temperature gradients, as evident from Figures 6-11. If the continuity diaphragm and beam end cracking shown in these figures is typical of prestressed concrete girders made continuous for composite loads one wonders how the compression force in the bottom of the girder ends can be developed if concrete is not bearing against concrete.

Table 7. Comparison of Simply Supported and Continuous Structure

	CLL*	SS**	Percentage (CLL/SS)
Live Load + Impact	1550 k-ft	1620 k-ft	95.7%
Rail & Overlay	197 k-ft	492 k-ft	40.0%
Non-Composite Dead Load	2872 k-ft	2872 k-ft	100.0%
Total Load	4619 k-ft	4984 k-ft	92.7%
Composite Load/Total Load	0.378	0.424	89.2%
f_c (bottom tensile)	4300 psi	4806 psi	89.5%
f_c (top comp.)	4345 psi	4396 psi	98.8%
M_u Required	6335 k-ft	7884 k-ft	80.4%
f'_{ci}	5825 psi	6535 psi	89.1%
f'_c	8390 psi	8349 psi	100.5%
Strands Required	62	66	93.9%
* Continuous for Live Load Superstructure ** Simple Span Superstructure			

Conclusions

Precast prestressed concrete bridge girders made continuous for live load (and other loads carried by the composite system) were at one time used in Texas, but they are no longer designed. This is because the reduction of expansion joints, and the associated reduction in structural deterioration, is more easily achieved by making the slab continuous and designing the precast concrete beams as simple spans. Also, any perceived savings in structure cost and/or section depth has never been realized. In fact the construction process is generally complicated by both the requirement to provide the more complicated bridge plan details discussed in this paper as well as the additional slab reinforcement details not discussed herein but certainly required to

develop the tensile continuity force in the slab. Even with such measures, the documented inadequate anchorage of the bottom of the beam ends to the continuity diaphragms indicates that the assumed live load continuity has been compromised. Fortunately, existing structures of this type are adequate as designed because of the additional prestressing required to carry all loads via simple span action is minimal and the design specifications in place when the bridges were conceived are conservative, mitigating against a compromise of their inherent structural reliability.

Acknowledgements

References

TxDOT, "Section 23 — Prestressed Continuous for Live Load I-Beam Spans," *Bridge Design Manual* http://manuals.dot.state.tx.us:80/dynaweb/colbridg/des/@Generic__BookView, 12/2001.